DOWNSTREAM HYDROGEOMORPHIC IMPACTS OF EILDON RESERVOIR ON THE MID-GOULBURN RIVER, VICTORIA

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Little Eildon Reservoir (377 450 ML capacity) was built on the Goulburn River between 1915 and 1927 to supply irrigation water to the Goulburn–Murray Irrigation District. To meet increasing demands for irrigation, the larger Big Eildon Reservoir (3 390 100 ML capacity) was built immediately below the original dam between 1950 and 1955. Flow regulation by Little Eildon Reservoir resulted in a non-significant reduction in mean annual runoff; maintenance of the natural seasonal flow distribution despite increasing summer flows and decreasing winter flows; a changed probability distribution of mean daily flows such that high flows were reduced, moderate flows were increased and low flows were reduced in duration; and a decrease in downstream sediment load from 210 000 m^3/a to 12 300 m^3/a. Flow regulation by Big Eildon Reservoir resulted in a further reduction in mean annual runoff; a totally reversed seasonal flow distribution with maximum flows in summer and autumn and minimum flows in winter and spring; a further change in the probability distribution of mean daily flows which magnified those initiated by Little Eildon Reservoir; lower flood peak discharges for all return periods; and a further decrease in downstream sediment loads, from 12 300 m^3/a to 2140 m^3/a. Despite the massive reductions in downstream sediment loads no bed degradation was induced by impoundment because regulated flows and dam spills are incompetent to transport the bed material. Slight but spatially disjunct channel contraction has occurred in response to flood suppression. Bank erosion rates are very low due to a combination of flood suppression, bank protection works and willow plantings. Willow invasion has been triggered by a combination of flow regulation and river management works, and is developing into a serious problem.

THE mid-Goulburn River refers to the river channel between Eildon Pondage and Lake Nagambie (Fig. 1). This section is part of the 430 km long Goulburn River corridor which was proclaimed a Heritage River by the Land Conservation Council (1991). Eildon Reservoir has regulated streamflows throughout the mid-Goulburn River since 1922 (Speedie 1948). However, the downstream effects of Eildon Reservoir on channel stability have not been assessed previously although flow regulation has often been blamed for causing river bank erosion (Hills 1975; Land Conservation Council, 1991). Furthermore, recent work on the downstream environmental impacts of Eildon Reservoir has concentrated on wetland inundation and water quality (Gippel et al. 1991; Gippel & Finlayson 1993). The purpose of this paper is to assess the downstream impacts of Eildon Dam on the flow regime, sediment load and channel stability of the mid-Goulburn River. In particular, the effects of dam-induced changes in fluvial processes on channel morphology will be determined.

Petts (1980) categorised the downstream effects of dams in terms of three orders of impacts. First-order impacts cover the downstream effects of dams on streamflows, water quality and sediment loads, and determine the magnitude of river response. Petts & Lewin (1979) found that dams often cause a decrease in both:

(i) the magnitude, frequency and duration of flood flows, and
(ii) the quantity and calibre of the sediment load.

Second-order impacts refer to the changes in channel form resulting from the first-order impacts. Channel readjustment will only occur if the process changes are of sufficient magnitude to disrupt equilibrium. The scientific literature since the early part of this century is replete with examples of downstream channel changes subsequent to dam closure (see Petts 1979; Williams & Wolman 1984). Third-order impacts include the feedback effects of the morphological changes upon the ecology or vice versa. Stable or depositional sites are good seed beds for phreatophytes which often invade channels after flow regulation (Williams & Wolman 1984; Sherrard & Erskine 1991; Benn & Erskine 1994). The three orders of impact of Eildon Reservoir on the mid-Goulburn River will be outlined after first discussing the salient characteristics of the dam. This information is necessary to form the basis of river management strategies for the mid-Goulburn River.

EILDON RESERVOIR

Eildon Reservoir is located on the Goulburn River immediately downstream of the junction of the Goulburn and Delatite Rivers (Fig. 1) where the catchment area is 3885 km^2. The original impoundment at Eildon was known as Little Eildon or Sugarloaf Reservoir and was built between 1915 and 1927 (Knight 1948). Selected characteristics of the original dam and the resultant lake are contained in Table 1. In 1929 the rockfill on the upstream portion of the dam wall subsided over a length of 366 m when the reservoir was drawn-

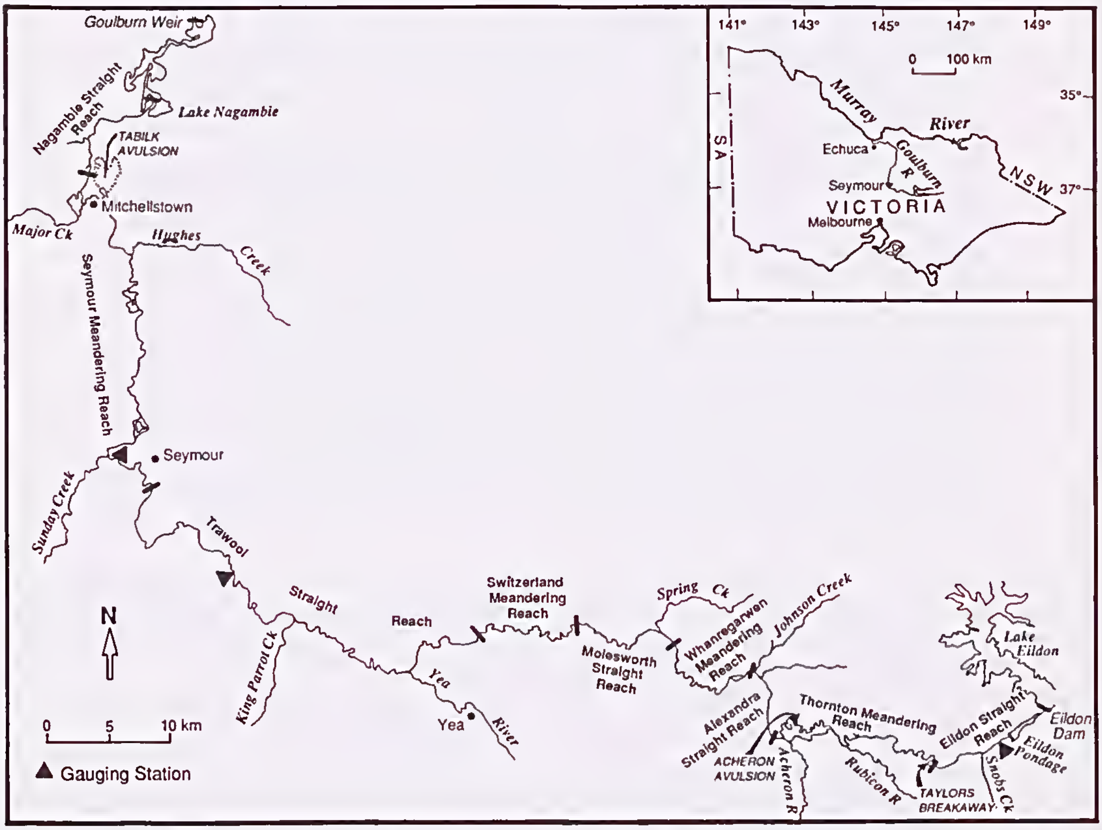

Fig. 1. Mid-Goulburn River between Eildon Reservoir and Lake Nagambie, showing alternating straight and meandering reaches.

	Original Eildon Dam, Little Eildon Reservoir	New Eildon Dam Big Eildon Reservoir
Storage capacity at full supply level (ML)	377 450	3 390 100
Surface area (ha)	3 075	13 750
Shoreline (km)	–	466
Maximum depth (m)	37.5	76.2
Mean depth (m)	12.3	23.9
Average annual inflow (ML/a)	1 917 850[1]	1 645 000[2]

[1] From Knight (1938). [2] From Powling (1980).

Table 1. Major physical and morphometric characteristics of Little and Big Eildon Reservoirs (from Knight 1938; Cadwallader 1980; Powling 1980; Collier 1986).

down from full supply level for the first time. (Knight 1938). This necessitated remedial measures which stabilised the dam (Knight 1938). The original dam was to be built in two stages with the second stage involving the raising of the dam wall by 16 m thus increasing the storage capacity threefold (Collier 1986). However, such enlargement was abandoned following the subsidence of the dam wall.

The purpose of the reservoir was to supply irrigation water to Lake Nagambie for distribution to the Goulburn–Murray Irrigation District. Water was released through either the main or power outlet and then conveyed down the natural channel to Lake Nagambie. Increasing demand for additional supply to the Goulburn–Murray Irrigation District resulted in the construction of the new, larger Big Eildon Reservoir immediately downstream of the original dam (Knight 1948; Speedie 1948). It was built between 1950 and 1955 and, when completed, was the largest reservoir in Australia. Selected characteristics of the new dam and the resultant lake are also contained in Table 1. Eildon Reservoir is a 'carry-over' dam which means that its storage capacity is larger than the mean annual flow. Sugarloaf Reservoir, on the other hand, had no carry-over capacity. Water can be released from the new dam at rates up to 9500 ML/d and is usually passed through two generators which have a total power output of 120 MW (Rural Water Commission undated). The original dam also had a power station but its total output was only 15 MW. The present hydropower releases are passed into a 5200 ML pondage below the new dam so that the flows can be re-regulated to:

(i) contain releases within the capacity of the channel,
(ii) reduce bank erosion and slumping, and
(iii) minimise danger to anglers and others using the river (Frost 1983).

Since 1959 Eildon Reservoir has been operated according to a set of rules known as 'Mark Operation', which include a target filling curve which aims to fill the storage by 1 October each year (State Rivers and Water Supply Commission 1981). If the reservoir is at target storage volume in May, there is a high probability of inflows between May and September being sufficient to fill the dam by 1 October (State Rivers & Water Supply Commission 1981). When inflows exceed the target, controlled releases are made at a rate dependent upon the prescribed allowable maximum flows at Seymour (these are not defined in State Rivers & Water Supply Commission, 1981). This constraint can, in fact, lead to releases being less than inflows, resulting in target levels being exceeded.

Detailed limnological surveys of Eildon Reservoir by Powling (1971, 1972, 1980) have established that the artificial lake is oligotrophic (low nutrient levels) and warm, monomictic (summer thermal stratification with holomixis or overturn at temperatures above 4°C at other times). Lake Eildon is thermally stratified between October and May. Overturn usually occurs in July when profundal nematods and rhizopods are found in surface water samples.

Thermal stratification is important because water is removed from the hypolimnion (the cold water zone) at a depth of 52 m for the outlets. As a result, the annual range in downstream monthly median water temperature has been reduced from 7.4–19.5°C to 9.9–13.5°C, with summer temperatures depressed and winter temperatures elevated above natural values (Gippel & Finlayson 1993).

FIRST-ORDER IMPACTS

The first-order impacts of Eildon Reservoir to be outlined below include downstream hydrologic changes and reduced sediment loads.

Hydrologic changes

Little Eildon Reservoir commenced storing water in July 1922 and Big Eildon Reservoir, in June 1955. Therefore, where data exist, the hydrologic records will be split into the pre-dam period (before July 1922), the Little Eildon Reservoir period (July 1922 to May 1955) and Big Eildon Reservoir period (June 1955 to September 1991). In this section changes in annual runoff, monthly runoff, mean daily discharge and flood peak discharge will be determined.

Annual runoff. The gauging station on the Goulburn River at Eildon commenced on 1 January 1916 and has operated continuously since then. The present gauge is located 800 m downstream of the regulating weir. The Rural Water Corporation has estimated 'natural' streamflows at the Eildon gauge since July 1922 by the following equation:

$$Q_N = \delta S + Q_R + E \qquad (1)$$

where Q_N is estimated natural flow at Eildon,
δS is change in lake storage,
Q_R is regulated flow at Eildon, and
E is evaporation from the reservoir surface.

These estimated natural streamflows have been tabulated on a monthly basis and used in the following analyses. This data set was *not* used in the previous hydrologic work on Eildon Reservoir by Gippel et al. (1991) and Gippel & Finlayson (1993).

Between July 1922 and May 1955 when Sugarloaf Reservoir was operational, the variance of annual regulated flow was not statistically significantly ($\alpha = 0.05$) different to the variance of annual estimated natural flow (F test). Although the mean annual regulated runoff was 39 614 ML less than the mean annual natural runoff, this difference is not significant ($\alpha = 0.05$) according to a t-test. This reduction in runoff equates to an evaporation loss of 1288 mm/a from Little Eildon Reservoir, assuming that the dam was always at full supply level.

Between June 1955 and September 1991, the variance of annual regulated flow was significantly less than the variance of annual natural flow. As the variances of the two data sets are not equal, a t-test cannot be used to assess differences in means. Therefore, the Z-test (Crow et al. 1960) was used and showed that the reduction in mean annual runoff of 122 902 ML by flow regulation was not significantly different to the mean annual natural runoff. This reduction in runoff equates to an evaporation loss of 821 mm/a from Big Eildon Reservoir, assuming that the dam was always at full supply level. This discrepancy in the two evaporation estimates for Little and Big Eildon Reservoirs can be explained by greatly reduced summer evaporation from the deeper Big Eildon Reservoir (Garrett & Hoy 1978).

Monthly runoff. The Rural Water Corporation data set used above was also analysed for changes in the variance and mean between regulated and estimated natural flows for each month. Again the data was split into the two time periods covering the operation of Little and Big Eildon Reservoirs. The same statistical tests were used as in the above section. The results for each month and for both time periods are summarised in Table 2.

Figure 2A shows the changes in mean monthly regulated and natural flows during the operation of Little Eildon Reservoir. Clearly, regulated flows significantly exceeded natural flows between December and April, inclusive during the irrigation season (Table 2). The period May to September marked the replenishment of stored water released for the preceding irrigation season.

Figure 2B shows the changes in mean monthly regulated and natural flows during the operation of Big Eildon Reservoir. In general terms, the hydrologic effects of Big Eildon Reservoir on monthly flows are the same as for Little Eildon Reservoir but the magnitude and hence, significance of the changes is much greater. Furthermore, while Little Eildon Reservoir influenced the seasonal flow distribution, the natural pattern was maintained with high winter and spring flows and low summer and autumn flows. On the other hand, Big Eildon Reservoir has totally reversed the natural seasonal flow pattern with maximum flows in summer and autumn, and minimum flows in winter and spring (Gippel et al. 1991; Gippel & Finlayson 1993).

Month	Sugarloaf Reservoir July 1922– May 1955		Eildon Reservoir June 1955– September 1991	
	Variance	Mean	Variance	Mean
January	*	*	*	*
February	*	*	*	*
March	N.S.	*	*	*
April	*	*	*	*
May	*	N.S.	*	*
June	N.S.	N.S.	*	*
July	N.S.	*	*	*
August	N.S.	*	*	*
September	N.S.	N.S.	N.S.	*
October	N.S.	N.S.	N.S.	*
November	N.S.	N.S.	N.S.	*
December	N.S.	*	N.S.	*

*—Significant at $\alpha < 0.05\%$.
N.S.—Not significant at $\alpha = 0.05\%$.

Table 2. Changes in the variance and mean between monthly regulated flow and monthly natural flow. See text for further details.

Flow durations. Flow duration curves based on mean daily discharge were prepared for the above three time periods. Fig. 3A shows the curves for each of these periods. Although the pre-dam data are used as an index of natural flow conditions, it must be stressed that the record is very short and contains two wet years (1916 and 1917). Little Eildon Reservoir truncated all flows above 82 000 ML/d, decreased the magnitude of flows with durations less than 36%, increased the magnitude of flows with durations between 36 and 87% and decreased the magnitude of flows with durations greater than 87% (Fig. 3A). The larger flows with durations between 36 and 87% (600–4000 ML/d) coincide with the irrigation releases. Big Eildon Reservoir further truncated high flows with no discharges greater than 46 200 ML/d having been recorded between

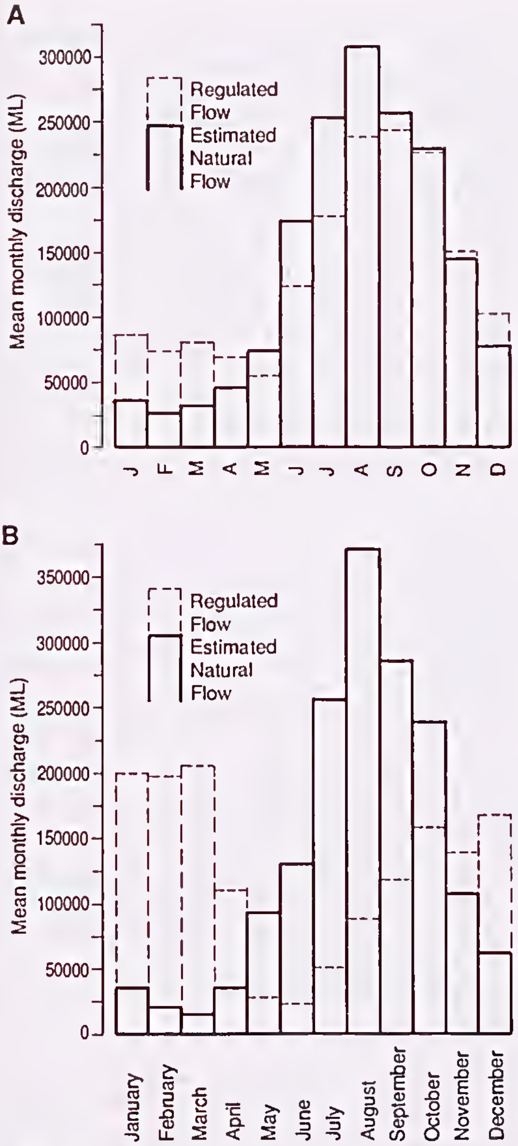

Fig. 2. A, Changes in mean monthly regulated flow and mean monthly natural flow at the Eildon gauging station between July 1922 and May 1955. B, Changes in mean monthly regulated flow and mean monthly natural flow at the Eildon gauging station between June 1955 and September 1991.

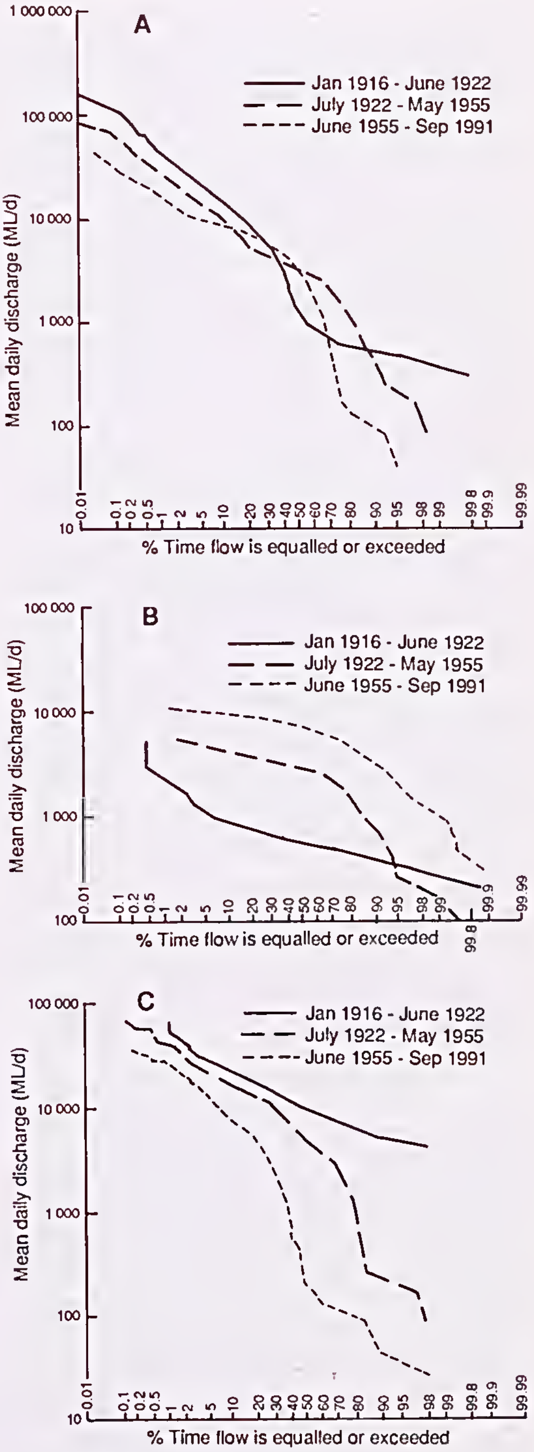

Fig. 3. A, Flow duration curves based on mean daily discharge at the Eildon gauging station for the periods January 1916 to June 1922 (natural conditions), July 1922 to May 1955 (Sugarloaf Reservoir) and June 1955 to September 1991 (Eildon Reservoir). B, Flow duration curves based on mean daily discharge for March at the Eildon gauging station. C, Flow duration curves based on mean daily discharge for August at the Eildon gauging station.

1955 and 1991. In comparison with the natural flow duration curve, Big Eildon decreased the magnitude of flows with durations less than 29%, increased the magnitude of flows with durations between 29 and 69% and decreased the magnitude of flows with durations greater than 69%. In comparison with the Little Eildon flow duration curve, Big Eildon further decreased the high flows (>8200 ML/d), augmented the moderate flows (3500–8200 ML/d) and further decreased the low flows.

To assess changes in the seasonal flow distribution caused by Little and Big Eildon Reservoirs, flow duration curves based on mean daily discharge were prepared for each month. The results are very consistent and are illustrated in Figs 3B and 3C. During the irrigation season, flow regulation has resulted in the wholesale *upward* displacement of the flow duration curve as shown for March in Fig. 3B. Under existing conditions, mean daily flow of a given duration is about an order of magnitude *greater* than under natural conditions.

Flow regulation has resulted in the storage of high winter flows and the consequent wholesale *downward* displacement of the flow duration curve as shown for August in Fig. 3C. The curves for Little and Big Eildon Reservoirs increasingly diverge from the curve for natural conditions for durations greater than about 20%. The maximum decrease in discharge for a given duration is greater than two orders of magnitude.

Flood frequency. An automatic water level recorder was first installed at the Eildon gauge in June 1953. Before then, the gauge was daily read. As a result, peak instantaneous discharges are only available at this site since 1954. Therefore, the following flood frequency analyses at Eildon were undertaken using maximum mean daily flow.

Figure 4A shows the annual series flood frequency curves for the periods 1922–54 (Little Eildon Reservoir) and 1955–86 (Big Eildon Reservoir). The method of Dalrymple (1960) was used with the modification that plotting positions were calculated by the Gringorten (1963) equation because it is an unbiased formula for the adopted Extreme Value I distribution (Cunnane 1978; Bell et al. 1989). This method was used in preference to the log Pearson Type III distribution adopted by State Rivers & Water Supply Commission (1981) and Gippel et al. (1991) so that the results could be directly compared with the published geomorphic literature. Clearly, the enlargement of the original dam has reduced greatly flood magnitudes for a given frequency. The percentage decrease in flood magnitude for various return periods since 1955 range between 60 and 72%. A return period of 1.58 years for an Extreme Value I distribution corresponds to the mode of the distribution and a return period of 2.33 years corresponds to the mean (Gumbel 1958). It has been argued that floods of this frequency correspond to the 'dominant' or 'channel-forming discharge' (Wolman & Leopold 1957; Wolman & Miller 1960; Leopold et al. 1964; Dury 1973). Reductions in maximum mean daily flow of 65–72% for floods of these return periods closely agree with the previous results of State Rivers & Water Supply Commission (1981) and Gippel et al. (1991). It should also be emphasised that the flood frequency curve for natural floods would plot above the curve for 1922–54. However, the pre-dam record is too short to undertake flood frequency analysis.

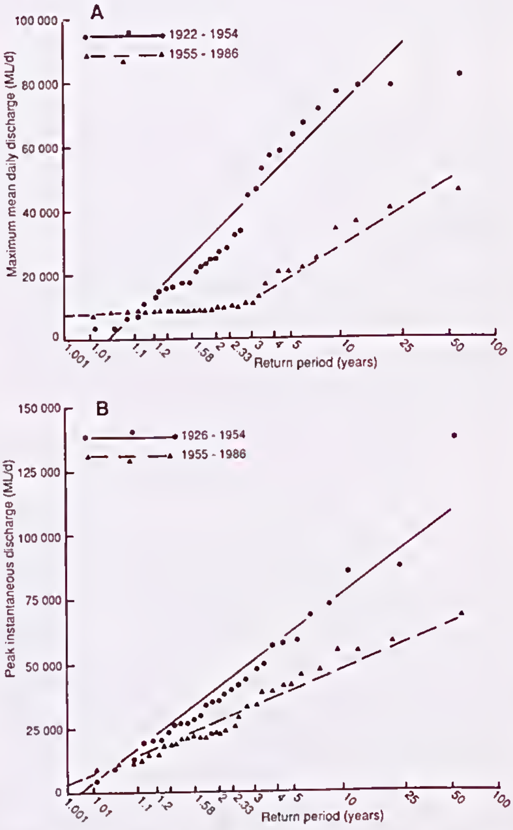

Fig. 4. A, Annual series flood frequency curves for the periods 1922–54 (Sugarloaf Reservoir) and 1955–86 (Eildon Reservoir) at the Eildon gauging station. B, Annual series flood frequency curves for the period 1926–54 (Sugarloaf Reservoir) and 1955–86 (Eildon Reservoir) at the Trawool gauging station.

Changes in flood frequency were also investigated at the downstream gauging station, Goulburn River at Trawool (Fig. 1), where the catchment area is 7335 km^2. A continuous record has been obtained since November 1925. However, some flood peaks were not recorded although the maximum mean daily discharge was. Therefore, the missing annual floods were estimated by regressing peak instantaneous discharge (Y) against maximum mean daily discharge (X) and the following equation was obtained:

$$Y = 250.97 + 1.037X \quad (2)$$
$$r = 0.998 \quad \alpha < 0.001$$
$$n = 50$$

Figure 4B shows the flood frequency curves for the periods 1926–54 and 1955–86 at Trawool and clearly demonstrates that Big Eildon Reservoir has also decreased flood peak discharge for all return periods although the catchment area is 1.89 times that at Eildon. Flood runoff from the unregulated tributaries between Eildon and Trawool has reduced the effect of Big Eildon, with reductions in flood peak discharge for various return periods ranging between 32 and 38%. Although Gippel et al. (1991) reported results for this station, they did *not* use peak instantaneous discharge for their analyses.

State Rivers & Water Supply Commission (1981) undertook a detailed flood study at Seymour (Fig. 1), where the catchment area is 8601 km^2 (2.21 times the catchment area at Eildon Reservoir). For return periods between 2 and 100 years, peak flows were reduced by 20% which represents a lowering of flood levels of about 0.3 m. Therefore, Big Eildon Reservoir is likely to have reduced flood peak discharges throughout the mid-Goulburn River.

Changes in downstream sediment loads. Sediment trap efficiency refers to the proportion of the incoming sediment load deposited in a reservoir. Some fine-grained sediment is usually transported through a storage and passed out of the valves or over the spillway. However, all of the incoming sand and gravel are trapped in large dams. The sediment trap efficiencies of Little and Big Eildon Reservoirs have been estimated by the methods of Brune (1953). These methods were chosen because Erskine (1985) found 'a close correspondence' between the trap efficiencies estimated by Brune's (1953) design procedures and that calculated by a before and after dam comparison of measured suspended sediment loads for Glenbawn Dam, NSW. Little Eildon Reservoir had a trap efficiency of 93.0–95.3% depending on whether the capacity–watershed or capacity–inflow ratio was used. Big Eildon Reservoir has a trap efficiency of 98.5–99.5%. Clearly, both Little and Big Eildon Reservoirs have trapped most of the incoming sediment.

The reduction in downstream sediment loads can be quantified from the measured rates of dam sedimentation (Joseph 1953a, 1953b, 1960; Abrahams 1972) and from the estimated sediment trap efficiencies. Joseph (1953a, 1953b, 1960) found that the measured mean sedimentation rate in Little Eildon Reservoir was 50.8 m^3/km^2/yr between 1927 and 1953. Therefore, if it is assumed that the sediment trap efficiency of Little Eildon Reservoir was 94.15% (mean of the estimates determined by the capacity–watershed and capacity–inflow ratio methods), the total sediment yield was 53.96 m^3/km^2/a or 210 000 m^3/a. As 94.15% was trapped in Little Eildon Reservoir, the mean annual sediment yield at the Eildon gauge between 1927 and 1953 was only 12 300 m^3/a. Abrahams (1972) found that the mean annual sedimentation rate in Big Eildon Reservoir in 1969 was 54.51 m^3/km^2/a. If the sediment trap efficiency is 99% (mean of the estimates determined by the capacity–watershed and capacity–inflow ratio methods), the total sediment yield was 55.06 m^3/km^2/a or 214 000 m^3/a which agrees closely with the sediment yield estimate for Little Eildon Reservoir. As 99% was trapped in Big Eildon Reservoir, the mean annual sediment yield at the Eildon gauge was only 2140 m^3/a. Therefore, before Little Eildon Reservoir was constructed, the Goulburn River at Eildon transported about 210 000 m^3/a of sediment. Little Eildon Reservoir reduced this sediment load to 12 300 m^3/a and Big Eildon Reservoir further reduced it to only 2140 m^3/a.

SECOND-ORDER IMPACTS

Second-order impacts refer to dam-induced channel changes. The hydrologic changes, particularly the reduced flood peak discharges, combined with the markedly reduced sediment loads are of such a magnitude that the pre-dam channel equilibrium may have been disrupted and consequently channel changes may have been initiated. Rivers respond to flow regulation in a complex manner (Petts 1979; Williams & Wolman 1984; Erskine 1985; Sherrard & Erskine 1991). Nevertheless, bed degradation or progressive bed erosion over time has been reported below many dams (Lane 1934; Petts 1979; Galay 1983). Furthermore, channel contraction by the formation of benches or berms within the pre-dam channel often occurs because of reduced downstream flood flows (Gregory & Park 1974; Sherrard & Erskine 1991; Benn & Erskine 1994). Channel pattern refers to river morphology as seen from the air or channel planform. As discharge and sediment load are known to be important controls on channel pattern (for example, Leopold & Wolman 1957), it would be expected that channel pattern will change when discharge and sediment load are altered drastically by flow regulation. In the remainder of this section, the impacts of Little and Big Eildon Reservoirs on bed degradation, bed mobility, channel contraction and river pattern changes on the mid-Goulburn River will be assessed.

Bed degradation

Degradation below dams has been known for some time. Lane (1935: 836), in the first of a series of papers on the topic in *Engineering News Record*, explained it thus:

> 'When a dam is constructed in a stream with a bed of movable material, part of the material which the stream transports will be deposited in the backwater area of the reservoir. The flow passing the dam, having been partly relieved of its load, will pick up material from the river bed below the dam and thus cause a retrogression of the bed level there.'

This can be explained by reference to the sediment transport continuity equation:

$$O_S = \delta S + I_S \quad (3)$$

where O_S is the sediment output from a reach of river,
I_S is the sediment input to the same reach of river, and
δS is the change in sediment storage within the reach.

For a channel to be stable, its dimensions should vary within a narrow range about a well-defined mean condition. When this is the case, O_S will equal I_S and δS will vary within small limits. Degradation depends only on the bedload component of the total sediment load. When a large dam is built, the bedload input to the downstream channel is reduced to zero, once any construction-mobilised sediment has been removed. Therefore, if there is any bedload transport out of the downstream reach of channel, it must be entrained from either the bed or banks of the channel. Bed entrainment causes degradation. Degradation starts at the outlet works/spillway and progresses downstream over time (Galay 1983). Rates of degradation >0.15 m/a have been reported (Lane 1934; Petts 1979). For degradation to occur, regulated flows must be capable of entraining the bed material. When flow regulation results in reduced downstream flood flows, as in the case of Little and Big Eildon Reservoirs, degradation may not occur.

The Rural Water Corporation has not monitored the response of the Goulburn River to upstream impoundment. Therefore, the rating curves for the three gauging stations on the mid-Goulburn River have been analysed to indirectly determine whether bed degradation has occurred. Specific gauge plots show variations in gauge height over time for the same discharge (Blench 1969). All data have been converted to the same gauge zero for the whole period of record at each station and all stations have natural gauge controls. Fig. 5 shows the specific gauge plots for discharges of 1000 and 10 000 ML/d at Eildon and 2000 and 10 000 ML/d at Trawool and Seymour. These discharges were chosen to cover the range of regulated flows. The Eildon plot (Fig. 5A) only covers the period since 1953 when the present gauge site was used. Clearly, there have been only minor changes in gauge height for the same discharge over this time, indicating that the channel has been very stable during the period that Big Eildon Reservoir has been operational. Rating curves are also available for the other two gauging sites at Eildon since April 1933. *No change* in the rating curves at both sites were found. Therefore, if the Goulburn River at Eildon has degraded in response to impoundment it must have occurred before 1933. This is unlikely because the channel is cut into bedrock (Thomas 1947).

The specific gauge plot at Trawool (Fig. 5B) also shows that the Goulburn River there has been remarkably stable since 1926. At Seymour (Fig. 5C), the location of the gauge was changed in 1968 and there have been more rating changes. Nevertheless, the data still do not exhibit a *definite* trend and contrast greatly to the specific gauge plots in Erskine et al. (1990) for selected unstable rivers in the Gippsland Lakes catchment. It would, therefore, appear that the mid-Goulburn River has been stable despite substantial flow regulation.

Bed mobility

Erskine (1985) found that channels are stable following upstream impoundment when regulated flows do not exceed the threshold of motion of the bed material. To determine if this is the case on the mid-Goulburn River, the competence of regulated flows was determined at each gauging station. The particle size characteristics of the bed material were determined by carrying out gravel counts according to the grid-by-number technique of Wolman (1954) at each gauge. The b-axis diameter of at least 100 gravel clasts was measured on submerged side bars and riffles at each site. The competence of maximum regulated flows (assumed to be 10 000 ML/d) was determined by the Meyer-Peter and Müller (1948) criterion at each gauging station. Effective diameter of the bed material was equated to mean size. Regulated and bank-full flows are *not* competent to mobilise the bed material at all stations. Therefore, the lack of degradation on the mid-Goulburn River since dam closure is explained by the very infrequent occurrence of threshold of motion conditions for bed material transport.

The only sections of the mid-Goulburn River which have degraded in recent years are located near gravel extraction sites at Seymour and Alexandra. Degradation at these sites has been caused by extraction creating local sediment transport discontinuities (Erskine 1990).

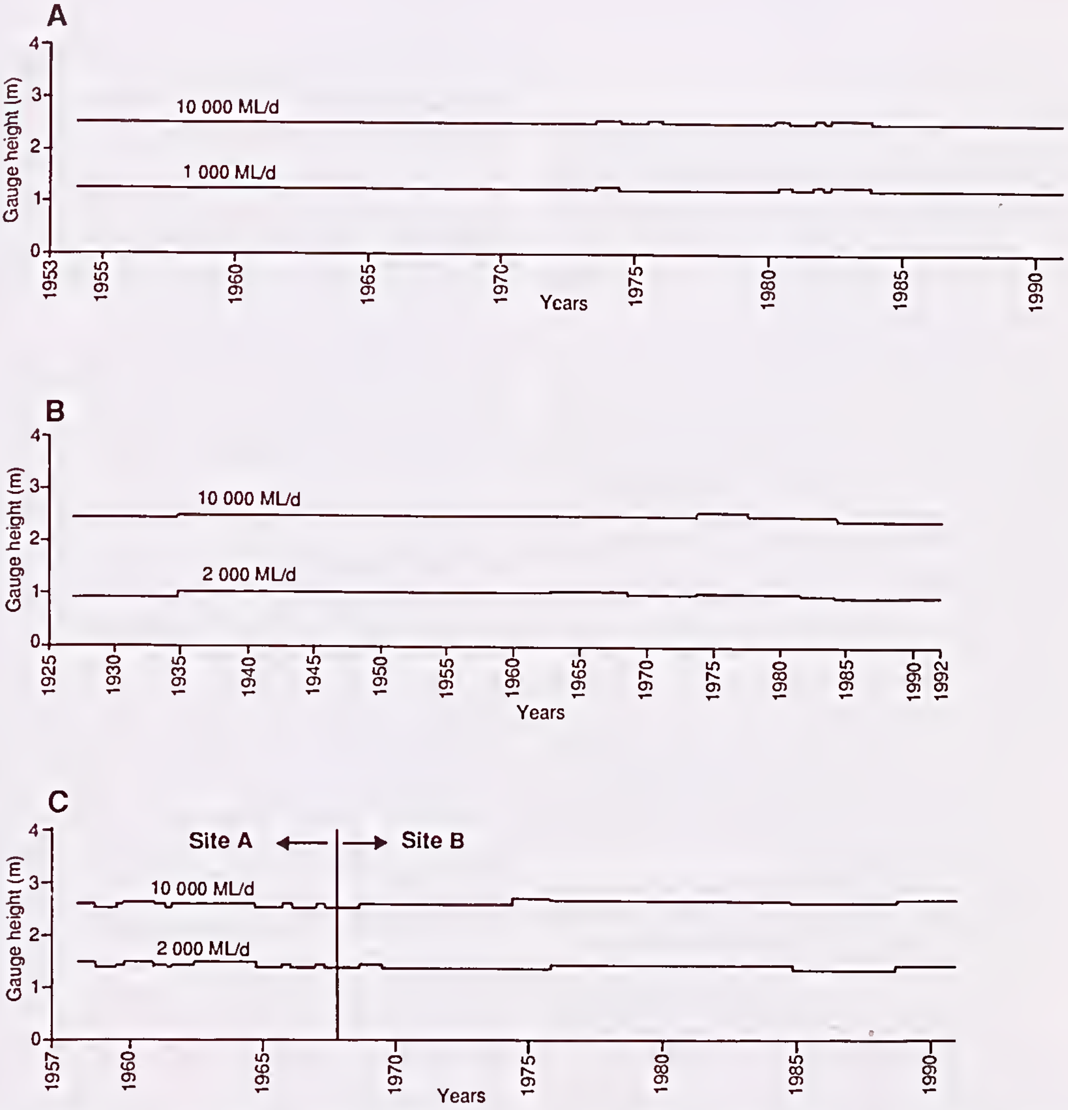

Fig. 5. Specific gauge plots. A, Eildon gauging station. B, Trawool gauging station. C, Seymour gauging station.

An armour layer is a surficial, thin, often monolayer of coarse bed material overlying finer sediment (Erskine et al. 1985; Erskine 1985, 1992). It is generally both coarser and better sorted than the subsurface sediment (Gomez 1984; Erskine 1992). The armour layer veneers the bed surface and hence protects the underlying finer sediment from erosion. Irrigation flows during the field work phase of this study prevented a detailed sedimentological study of the bed material in the mid-Goulburn River. Nevertheless, it appears from field inspections that the bed is armoured. If this is the case, the natural armour coat must be retained intact to prevent localised degradation.

Channel contraction

Channel width is adjusted to dominant discharge according to a simple power function. Kellerhals (1967) found that, on armoured gravel-bed streams, bankfull width is related to dominant discharge by the following equation:

$$W = 0.635Q^{0.5} \qquad (4)$$

where W is channel width, (m), and
Q is dominant discharge (m^3/s).

Therefore, if dominant discharge decreases due to flow regulation, as has occurred on the mid-Goulburn River, channel width should decrease, provided there is a source of sediment for deposition within the overwide pre-dam channel. From the above equation, it is predicted that the channel will contract by up to 59 m because the mean annual flood has been reduced by up to 72%. Although there are no permanently marked, long term cross sections on the mid-Goulburn River to test this prediction, the following indirect evidence suggests that recent discontinuous channel contraction has occurred:

(i) the river banks are well vegetated and stable;
(ii) low berms, benches and bars of sand, gravel and mud are discontinuously present along the side of the channel below the river bank in many locations;
(iii) trees growing on these berms, benches and bars are relatively young as shown by their small diameters and low heights; and
(iv) soils developed on these landforms correspond to the stratic stage alluvial soils of Walker & Coventry (1976) which are known to be relatively young (<200 years).

The berms, benches and bars are preferentially located near local sediment sources, such as unregulated tributary junctions, cutoffs or formerly eroding banks. A similar situation has been documented on the Cudgegong River below Windamere Dam in New South Wales (Benn & Erskine 1994). However, these in-channel benches on the mid-Goulburn River are spatially disjunct and very narrow because of the limited sediment supply.

River pattern changes

There have been two types of channel pattern changes on the mid-Goulburn River, viz lateral migration/bank erosion and channel avulsions. Each of these will now be discussed in turn.

Lateral migration. The Master Plans prepared for the three former River Improvement Trusts which carried out river management works on the mid-Goulburn River, all refer to bank erosion as a problem and as one of the reasons leading to the formation of the Trusts (Ian Drummond & Associates 1984a, 1984b; Willing & Partners 1984). While snags, gravel bars and regulated flows were mentioned as significant causes of bank erosion, lateral migration and meander development were also recognised as being significant.

The mid-Goulburn River exhibits alternating reaches of straight and meandering channels (Thomas 1947; Erskine et al. 1993). Fig. 1 shows the location of these reaches. It must be stressed that, while it is relatively easy to identify these alternating straight and sinuous sections, the boundary between them is far from clear cut. Therefore, the boundaries shown in Fig. 1 should be viewed as being approximate only. The channel patterns adopted in Fig. 1 are taken from Leopold & Wolman (1957) who recognised straight, meandering and braided channels. Straight channels had a sinuosity (ratio of channel length to valley length and used as an index of the degree of meandering) of less than 1.5 and meandering channels, greater than or equal to 1.5. The reasons for these alternating straight and meandering sections are unclear. Measurements of valley slope from the State Rivers & Water Supply Commission's 1935 Goulburn River Survey Plans (30023 to 30028) for the various reaches showed little, if any difference between straight and sinuous sections. Therefore, valley slope does not explain the channel pattern changes in contrast to the situation on the Mississippi River reported by Schumm et al. (1972). Although valley width is less on most straight reaches than on most meandering reaches, this is not always the case. If the straight reaches were formerly meandering and have straightened by cutoffs then the rate of meander development must be very slow.

Comparison of the first surveys of the mid-Goulburn River (Pickering 1841; Pininger 1856; Anon. 1860) and the State Rivers and Water Supply Commission's 1935 surveys with present channel conditions shows a few cutoffs and avulsions but relatively minor lateral migration. In fact, the bank erosion rates on the mid-Goulburn River are less than Hooke's (1980) minimum rates measured on rivers of comparable size throughout the world.

The density of riparian trees, particularly willows has increased greatly as a result of plantings by the former River Improvement Trusts and by the present North Central Waterways Management Board. Willows and, in some cases, River Red Gums, have formed extensive root mats. Smith (1976) has demonstrated that thick root mats can increase sediment resistance by 10 000 times over a bare bank. Flow regulation, by decreasing peak discharges and hence stream power, and river management works, by planting trees on the banks and by placing rockfill and other structural works, have increased bank resistance. Therefore, lateral migration and bank erosion rates are now very slow on most of the mid-Goulburn River.

Channel avulsions. Channel avulsions are the wholesale abandonment of one river course for another at a lower level on the floodplain (Allen 1965). There has been one recent avulsion on the mid-Goulburn River at Acheron (Thompson 1938), and another was occurring at Taylors Breakaway near Thornton (Turnbull 1957), before engineering works were undertaken to stop the river diversion. The Acheron avulsion probably occurred in July 1931 by the second largest flood to be passed through Little Eildon Reservoir (Erskine et al. 1993) and will not be discussed further.

Taylor's Breakaway is a crevasse, gulch or breach of the natural levee of the Goulburn River at the apex of a cutoff about 11 km downstream of Eildon Reservoir at the start of the Thornton meandering reach (Fig. 6). This cutoff occurred between the surveys of Pininger (1856) and State Rivers & Water Supply Commission (in 1935). Nevertheless, overbank flow still passed through Taylors Breakaway after the cutoff had been effected. The overbank flow split and either flowed down a series of floodplain depressions into the Rubicon River or through another series of depressions to Thornton (Fig. 6). The initial maximum releases from Eildon Reservoir caused substantial scour of the crevasse. To prevent an avulsion from occurring due to prolonged regulated flows, the State Rivers & Water Supply Com-

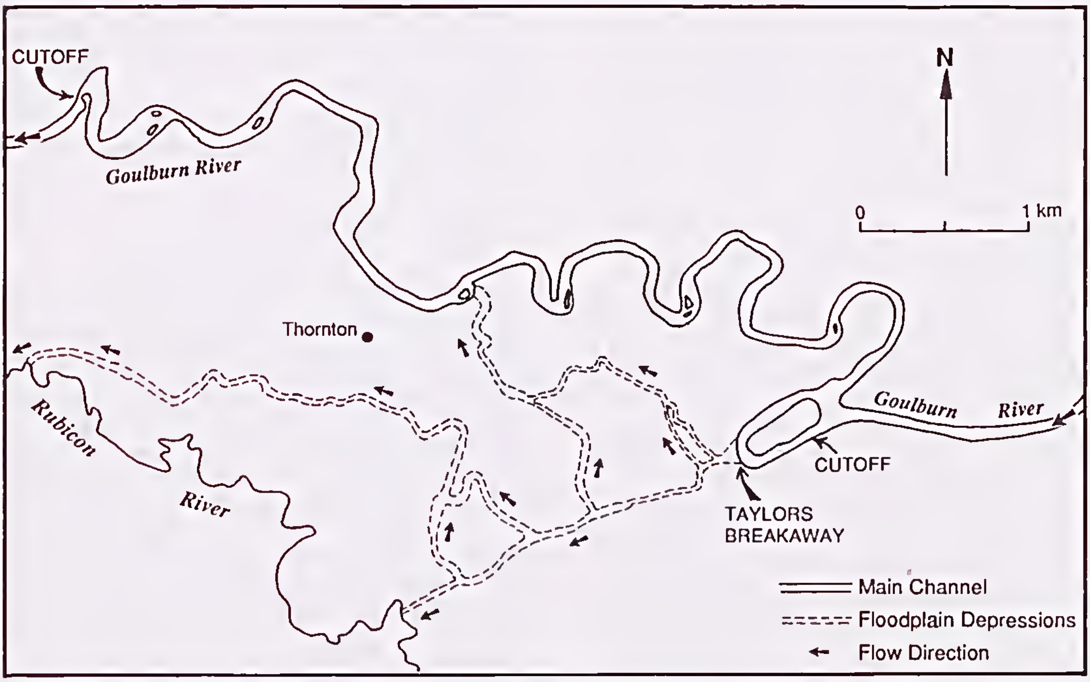

Fig. 6. Potential avulsion at Taylor's Breakaway. See Fig. 1 for location.

mission built a sheet pile weir at the crevasse. Turnbull (1957) discusses this structure in detail. Recent field inspections revealed that the sheet pile weir has successfully prevented a major avulsion from occurring. In this case, regulated flows would have caused an avulsion if appropriate engineering works had not been undertaken.

THIRD-ORDER IMPACTS

Third-order impacts reflect the feedback effects of the morphological changes upon the ecology or vice versa, and occur with a considerable time-lag in relation to the first-order changes of processes (Petts 1980). The most important third-order impact from a geomorphic perspective is vegetation encroachment on the regulated main stream. Although there are many other third-order impacts, these are solely of an ecological nature and are discussed elsewhere (see Walker et al. 1978; Baxter 1977; Walker 1985; Gippel & Finlayson 1993 for further details).

Vegetation encroachment

Regulated rivers are often invaded by vegetation because they have a stable substrate and because there is an absence of large disruptive floods. Furthermore exposed bars and benches with shallow water tables are good sites for phreatophytes. On the mid-Goulburn River, *Salix* spp., *Eucalyptus* spp. and *Acacia* spp. are common along many sections of channel. *Salix* spp. is a major problem on many regulated streams in Australia (Erskine 1985). Comparison of today's conditions with those depicted in old photographs taken by the various River Improvement Trusts clearly demonstrates that willows have invaded long sections of river. River Improvement Trusts planted willows for bank erosion control (Erskine et al. 1993) and many of the willow stands represent these extended plantings. The regulated flow conditions during the operation of Eildon Reservoir exhibit smaller flood peak discharges and reduced flood variability (Figs 4A and 4B). Therefore, the survival of large numbers of planted willows should have been predicted. While willows undoubtedly stabilise formerly eroding banks, they can rapidly develop into a problem. They can increase roughness significantly, accelerate deposition and reduce species diversity. Now that there are extensive but spatially disjunct stands of willows on a highly regulated stream they will invade the intervening areas to form a continuously willow-lined channel. The rate of invasion seems to be relatively slow with thick stands taking about 30 years to develop. Extensive willow control is necessary to avoid the loss of native species from the riparian corridor.

DISCUSSION AND CONCLUSIONS

The construction and operation of Little and Big Eildon Reservoirs has resulted in significant downstream hydrologic changes on the mid-Goulburn River. Gippel and Finlayson (1993) concluded that these hydrologic changes in combination with lowered spring and summer water temperatures alienated the Goulburn River between Eildon and Seymour from habitation by native fish species. While similar explanations of the demise of native fish on inland regulated rivers have been published (Cadwallader 1978), recent research has demonstrated that the iridovirus, epizootic haematopoietic necrosis (EHN), has also played a major role in the population decline of at least *Macquaria australasica, Galaxias olidus* and *Bidyanus bidyanus* (Langdon 1989). EHN is the first virus to be found in Australian fish (Langdon 1986) and the disease is characterised by necrosis of the renal haematopoietic tissue, liver, spleen and pancreas (Langdon & Humphrey 1987). While EHN is extremely infectious and pathogenic for the introduced *Perca fluviatilis*, some native species are also highly susceptible to in-water transmission and others are potential carriers and host species (Langdon 1989). EHN has been found in Lake Eildon and the Goulburn River downstream (Langdon & Humphrey 1987). Therefore, the well documented demise of native fish species in the mid-Goulburn River has most probably been caused by the interaction of hydrologic and water quality changes with the infectious and often pathogenic iridovirus EHN plus the introduction of exotic fish species (Cadwallader 1986).

Flow regulation has significant implications for river management. The substantial reduction in flood discharges has greatly reduced the extent and rate of bank erosion. Bank stabilisation works are not a contemporary priority issue on most of the mid-Goulburn River. Reduced bank erosion and the high sediment trap efficiency of Big Eildon Reservoir has reduced downstream sediment supply and flood suppression has reduced the frequency of, if not totally stopped, bed load transport on the mid-Goulburn River. Extractive industries are, therefore, removing a non-sustainable resource, inducing local bed erosion in the process (Erskine 1990). They should now be managed so that extraction is only allowed where it achieves river management objectives. Furthermore, if the bed of the mid-Goulburn River is armoured, then extraction will destabilise this protective coating. Further investigations of bed stability are clearly required.

Willow invasion of the riparian corridor is a major problem which has been partly induced by flow regulation. A riparian vegetation management plan is needed for the mid-Goulburn River to address the problems of increased resistance to flow, channel blockages, reduced species diversity, willow replacement, regeneration of native species, bank stability and habitat maintenance.

River management of the mid-Goulburn River should be carried out by a single authority with jurisdiction for the whole reach between Eildon Pondage and Lake Nagambie. River management issues, strategies and plans are similar for the whole reach and should be implemented by this single body.

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